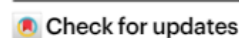


Variations in the Earth's rotation rate measured with a ring laser interferometer

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An exact knowledge of the instantaneous Earth's rotation rate is indispensable for accurate navigation and geolocation. Fluctuations in the length of sidereal day are caused by momentum exchange between the fluids of the Earth (namely, the atmosphere, hydrosphere and cryosphere) and the solid Earth. Since a multitude of different globally distributed and independent mass transport phenomena are involved, the resultant effect on the Earth's rotation is not predictable and needs to be continuously measured. Here we report the observation of minute variations in the rotation rate of the Earth at the level of five parts per billion, namely, with a resolution of a few milliseconds over 120 days of continuous measurements. We employ an inertial self-contained measurement technique based on an optical ring laser interferometer rigidly strapped down to the Earth's crust and operated in the Sagnac configuration. This large-scale gyroscope integrates over three hours for each data point, as opposed to an entire global network of Global Navigation Satellite Systems receivers and Very Long Baseline Interferometry that can only provide a single measurement per day.

Earth's rotation is usually perceived as a constant motion. However, when examined at a sufficiently high resolution, it exhibits small variations¹. The Earth is not a perfect sphere and the mass distribution is not homogeneous across the entire body of the Earth. The direct influence of the luni-solar gravitational attraction causes a retrograde diurnal polar motion². Effects from the tidal deformation³ cause length-of-day variations and give rise to diurnal and semi-diurnal tidal signatures in both polar motion and length of day. These perturbations in the Earth's rotation have amplitudes at 0.1 ppm, are readily observable and are well explained by theoretical models. When looking at the Earth's rotation at even higher resolution than these tidal signals, one can find another set of perturbations, which are not predictable. They arise from mass transport phenomena of the fluids of the Earth at a global scale, which exchange momentum with the solid part of the Earth. A prominent example is the El Niño southern oscillation, which develops from time to time every few years, inducing a pronounced seasonal effect. Smaller periodic variations have periods of around

nine and fourteen days. The length-of-day variations are the result of the combined effect of all the contributors to global mass transport, mostly the large-scale air-mass circulation patterns and, to a lesser extent, the ocean currents. It changes the Earth's spin with values of up to one millisecond over several days, corresponding to a signal of up to two parts in 10^8 in magnitude. The exact measurement of these perturbations provides an important constraint for geophysical models describing the integral effect of global mass transport.

Length-of-day variations correspond to variations in the orientation of Earth in space, and this is measured by a compass. For this matter, a star compass is usually employed, which is looking at the Universe outside. Astrometric measurements from the observation of stars provided the first indication for variations in the rotation rate of the Earth. The measurement techniques of space geodesy, namely, Very Long Baseline Interferometry (VLBI)⁴, Satellite Laser Ranging and Global Navigation Satellite Systems (GNSS), provide the measurements of the Earth's orientation at the resolution of a fraction of a

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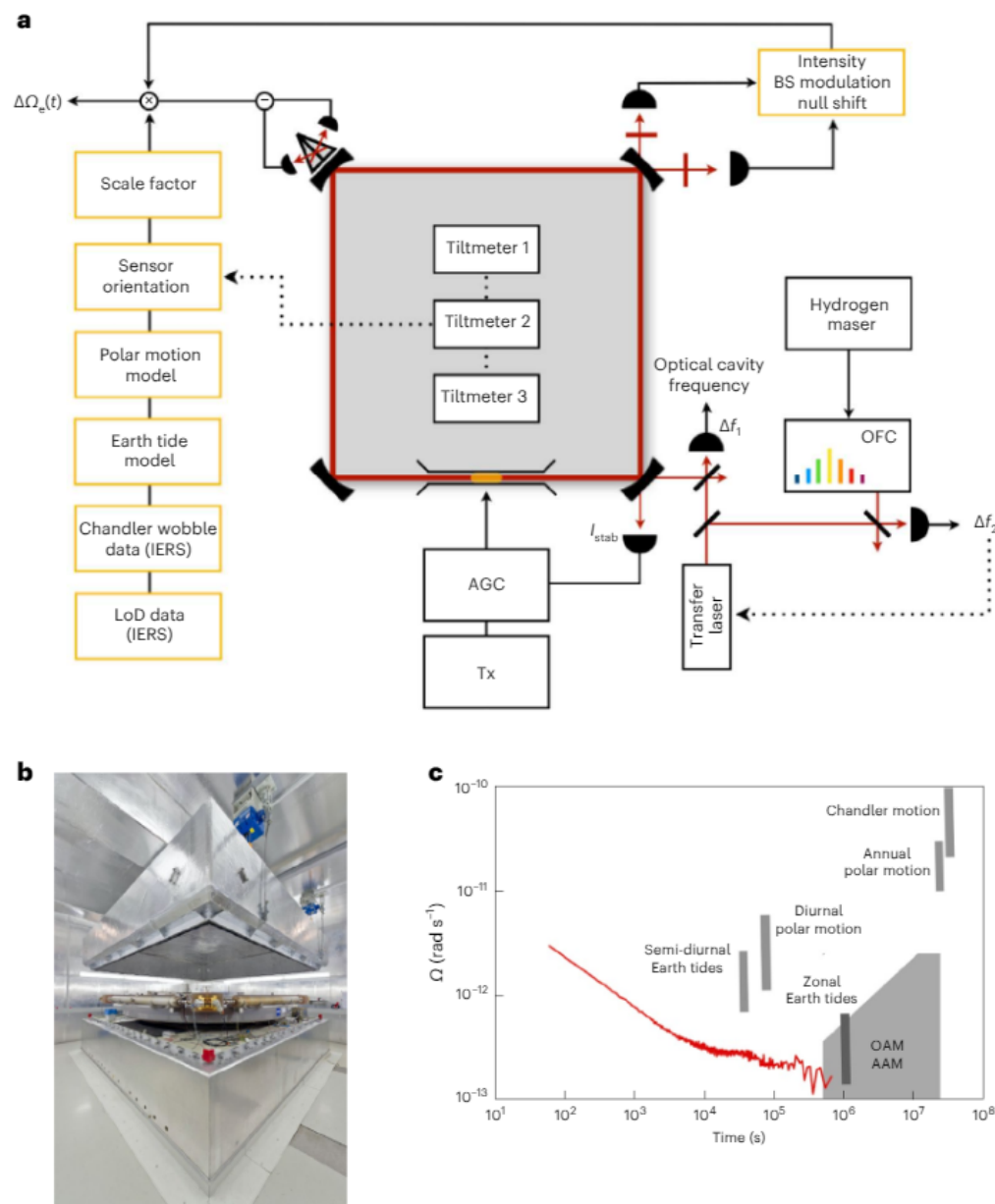


Fig. 1 | Instrumental design and observed sensitivity of the ring laser gyroscope **G. a**, The $4 \times 4 \text{ m}^2$ high-quality-factor ring laser cavity and the experimental layout is illustrated in a simplified block diagram. Four super mirrors rigidly fixed to a temperature-stable Zerodur base provide the necessary sensor stability. **b**, Photograph with the pressure-stabilizing vessel lifted up. **c**, Long-term ring laser resolution is presented in an Allan deviation plot

with respect to the approximate magnitude and frequency range of known geophysical excitations. The yellow boxes indicate the numerical processes, whereas the black boxes mark the instrumentation. OFC, optical frequency comb; AGC, automatic gain control; Tx, transmitter; OAM, ocean angular momentum; AAM, atmospheric angular momentum.

milliarcsecond. This is achieved by utilizing a network of several hundreds of GNSS receivers distributed over the entire globe. Additional VLBI measurements are required to tie these GNSS observations to the celestial reference frame of well-defined quasar positions. According to another work⁵, an alternative favourable approach would be the application of an inertial compass, which is entirely self-contained. However, until now, a sufficiently stable inertial platform with adequate sensitivity has not been demonstrated, although substantial effort has been undertaken⁶.

In contrast to translational velocities, rotational velocities can be measured in an absolute sense. This led to the speculation⁷ about the feasibility of an Earth-based inertial-rotation-sensing technology with sufficient resolution, where they mention that ‘come to think of it, no one

ever said the Earth’s rotation could not be measured with an apparatus in the comfort of a windowless basement’. Now, 31 years later, we present the successful inertial measurement of length-of-day variations in the frequency band around $1 \mu\text{Hz}$ or 14 days in period. From the list of potential sensor candidates, as discussed in ref. 7, a large ring laser gyroscope has turned out to be the system of choice⁸. Our single-component large gyroscope is located at the Geodetic Observatory Wettzell in Southern Germany (Fig. 1). The sensor exploits the Sagnac effect and represents a monolithic ring cavity, made from the low-thermal-expansion material Zerodur. Two laser beams propagate around a square contour in opposite directions. Under rotational motion, the effective cavity lengths are unequal and the superposition of the two laser beams produces a beat note, which is proportional to the rate of rotation⁸.

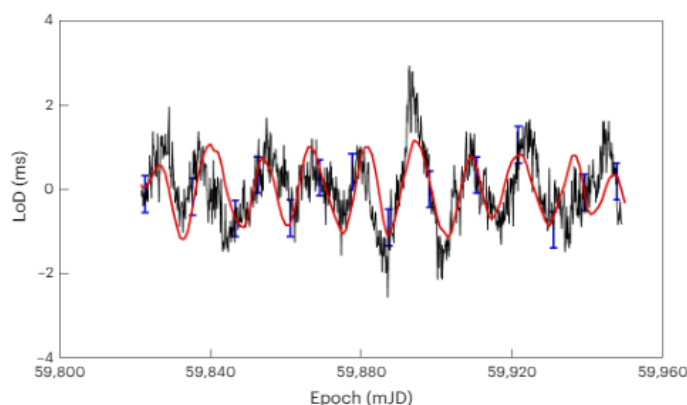


Fig. 2 | Observation of LoD signal (black) by the large ring laser gyroscope *G* at the Geodetic Observatory Wettzell as a function of time, represented in the modified Julian date (mJD). Comparison with the corresponding C04 data series¹² of the IERS (red) shows good agreement. Data are presented as mean of 180 values $\pm$ standard deviation. Some small systematic departures remain, mostly caused by limitations of the tiltmeters to provide unbiased local tilt effects of the gyro.

Unlike the VLBI and GNSS technologies, a single-component gyroscope, rigidly strapped down to the solid Earth, senses various geophysical signals, some of which are related to the rate of rotation experienced by the device, such as the length of sidereal day (LoD) signal reported here. Others are associated with polar motion^{9–11} and relate to the orientation of the instantaneous Earth's rotation axis. These latter signals manifest themselves by introducing a tilt to the area enclosed by the intracavity laser beams. The Earth's rotation is represented by a three-component vector Ω , where the norm of the z component represents the actual spin of the Earth and the x and y components account for the instantaneous orientation of the rotation axis (polar motion). A single-axis gyroscope, like our ring laser *G*, can only resolve one component of Ω . To infer the rate of rotation, we have to independently keep track of the local sensor tilt with high resolution. From Fig. 1c, we can see that the outstanding stability of the *G* ring laser is sufficient to provide the desired sensor resolution of the order of 5×10^{-13} rad s⁻¹ over at least one month. This is enough to capture the effects of the ocean angular momentum and atmospheric angular momentum on the Earth spin.

Results and data treatment

Results

The output of a ring laser gyroscope is a time series of the observed beat note between the counter-propagating single-longitudinal-mode laser beams of a travelling-wave optical resonator. The raw interferogram represents the rotational rate of the Earth biased by backscatter coupling, null-shift offsets and non-reciprocal effects from the laser gain medium. These can be corrected from the in situ measurements of additional operational parameters, as detailed in the subsequent sections. Since the large gyroscope is rigidly strapped down to Earth, it is subject to the tidal change of orientation, local tilt and polar motion including the Chandler wobble. We use measurements from local tiltmeters, geophysical models and observations from the C04 time series of the International Earth Rotation and Reference Systems Service (IERS)¹² to compute and remove these signals from our observations as well as the constant component of the Earth's rotation signal.

The dominant component of the LoD signal is in the frequency range around 1 μ Hz. Therefore, we apply a phase-preserving high-pass filter with a cut-off frequency of 300 nHz (a 39-day period) to our residuals and compare these with LoD from the C04 time series provided by the IERS. The result for more than 130 days of observation is shown in Fig. 2. Good agreement between the geometrical and inertial measurement techniques is obtained, although some small discrepancies

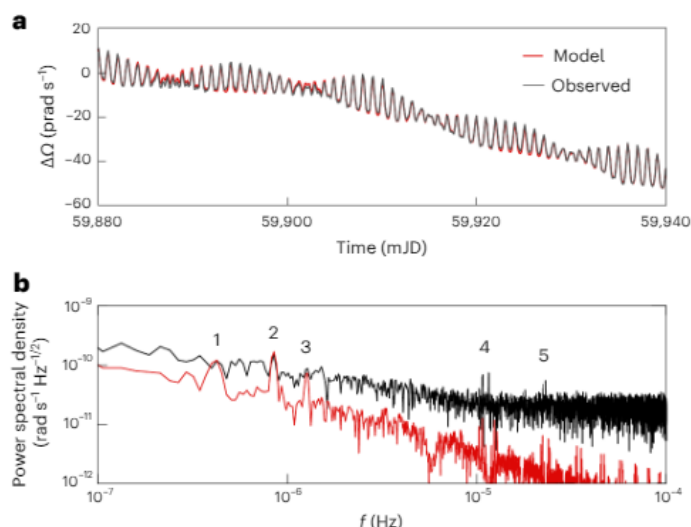


Fig. 3 | Ring laser observations in the time and spectral domain. a, b, Comparison of the observed (black) with the modelled (red) variation in the Earth's rotation rate in the time domain (a) and spectral domain (b). The spectral components, indicated by 1–3, have a period of 28, 14 and 9 days, respectively. The signals indicated by 4 and 5 are as yet unmodelled signal contributions from ocean loading and atmospheric tides. The four main contributors to the apparent polar motion, namely, the semi-diurnal Earth tides, diurnal polar motion, annual wobble and Chandler wobble, are comparatively large and have been removed from the observation in the spectral domain for better clarity. They are shown as observed in the time-domain representation. There is a near-perfect agreement between the observations and model.

remain. These systematic deviations are caused by small residuals of local effects, which have not been entirely captured by our auxiliary measurements, mostly due to limitations arising from the observed stability and sensor systematics from the group of tiltmeters.

Experimental layout

The laser gyroscope *G* consists of a 16.0023-m-perimeter ring cavity¹³, enclosing an area of 16.013 m². It is operated near the lasing threshold as a bidirectional, continuous-wave single-longitudinal-mode He–Ne gas laser. The gyro exhibits excellent spectroscopic properties, providing a laser linewidth as low as 7 μ Hz. Single-mode operation was ensured by using a Fabry–Pérot interferometer. *G* is horizontally placed onto a solid concrete pillar in an underground laboratory, anchored on bedrock at a latitude of $\theta = 49.099645^\circ$ N and a longitude of $\delta = 12.878005^\circ$ E. The coordinates are obtained from a local survey within the local surveying network of the observatory. Figure 1 shows a schematic of the hardware setup and the overall system design. Apart from the beat note of the Sagnac interferometer, we monitor the backscatter signal on each laser beam as well as the optical frequency in the cavity. For this, we utilize an optical frequency comb and a transfer laser to cope with the low-output-light level of the gyroscope. A pressure-stabilizing vessel encloses the gyro cavity. Several tiltmeters on the base plate of the gyroscope, each with a resolution of $\delta\phi < 1$ nrad, are used to keep track of the relative orientation changes with respect to the local gravity vector g . The beat note Δf of the two counter-propagating beams in the cavity is derived from the following ring laser equation:

$$\Delta f(t) = S\Omega(t) \sin \theta, \text{ where } S = \frac{4A}{\lambda P}, \quad (1)$$

and amounts to 348.5 Hz for the case of *G*. The quantity S is the scale factor of the apparatus, where A is the area in this equation, P is the perimeter enclosed by the laser beams, λ is the wavelength and θ is the orientation (as defined earlier). The common strategy to improve

the sensitivity of such a gyroscope is to make the area large and the cavity losses as small as possible. G can resolve 12 prad s^{-1} in 1 s (ref. 13). Since the ring laser has spherical mirrors and an active medium in the cavity, S requires several corrections¹⁴, namely, for the Goos–Hänchen displacement, refractive index of laser gas, dispersion of laser gas, mirror coatings and curvature of wavefront. We denote their inclusion by writing S' for the scale factor.

Non-reciprocal biases

Frequency pulling and pushing from backscatter coupling causes an intensity-dependent non-reciprocal bias $\Delta f_{\text{BS}}(t)$ on the observed beat frequency and has been corrected using the model presented in another work¹⁵. The two beams in the cavity consistently differ in intensity by less than 1%. This leads to a small time-varying offset $\Delta f_{\text{NS}}(t)$, usually referred to as the null-shift contribution. It is computed by applying a slightly modified version of the formalism introduced elsewhere^{16,17}.

With the null-shift corrections applied and the mean value of the Sagnac beat note $\bar{\Delta f}$ subtracted, we can convert the observed time series of the beat note into the respective rotation rate of the Earth, by applying the scale factor S' in the conversion.

$$\Delta \Omega_e(t) = \frac{(\Delta f(t) - \Delta f_{\text{BS}}(t) - \Delta f_{\text{NS}}(t)) - \bar{\Delta f}}{S' \sin \theta} \quad (2)$$

This result is presented in Fig. 3. The four main contributors, namely, the semi-diurnal Earth tides ($\Delta \theta_{\text{tide}}(t)$), the diurnal polar motion ($\Delta \theta_{\text{pole}}(t)$), the annual wobble and the Chandler wobble (combined as $\Delta \theta_{\text{IERS}}(t)$), are clearly visible. There is excellent agreement between the observations and theory. The complete model was computed by using routines from the SPOTL library³ for the semi-diurnal tides model, the diurnal polar motion model¹⁰ and the observations from the IERS¹² to account for the annual and Chandler wobble. These four signal contributors (Fig. 3) influence the orientation of the ring laser.

Tilt correction

Since the normal vector on the laser plane is not aligned with the Earth's rotation axis, variations in north–south orientation change the projection of the Earth's rotation vector onto the ring laser area. Tilts in the east–west orientation are not visible on a single horizontally orientated gyroscope component, because they enter as negligible small offsets to a $\cos(0^\circ)$ term. The obtained residuals discussed in the previous paragraph are either related to a change in projection of the rotation axis of the Earth or to a change in orientation of the ring laser plane. None of them reflects a change in the Earth's spin. To complete the list of contributing factors, we have to also include the non-tidal local tilt ($\Delta \theta_{\text{tilt}}(t)$), which accounts for deformations in the ring laser site from atmospheric loading, ground-water variation and other local tilt effects. A tiltmeter represents a pendulum, which is interrogated by a capacitive pickup system. It does not only sense tilts as it is also sensitive to mass attraction. Therefore, we have to apply appropriate corrections $\Delta \theta_{\text{att}}(t)$, computed from a global weather model, according to the procedure outlined elsewhere¹⁸. With all these corrections applied, our observation equation becomes

$$\Delta \Omega_e(t) = \frac{(\Delta f(t) - \Delta f_{\text{BS}}(t) - \Delta f_{\text{NS}}(t)) - \bar{\Delta f}}{S' \sin(\theta - \Delta \theta_{\text{tide}}(t) - \Delta \theta_{\text{pole}}(t) - \Delta \theta_{\text{IERS}}(t) - \Delta \theta_{\text{tilt}}(t) + \Delta \theta_{\text{att}}(t))} \quad (3)$$

Discussion

The Earth system is very complex with respect to the many processes involved, which interact with the global rotation rate of the Earth. This applies not only to the global water cycle and atmospheric forcing but it is also relevant to understand the dynamical processes within the Earth's interior. For many of these processes, a number of competing

theoretical models exist. The observation of the instantaneous Earth's rotation rate does not reveal all the details, but it provides an important constraint for the integral effect of all the processes taken together, both in amplitude and spectral distribution.

Our inertial compass G is now in the position to continuously detect this signal, in real time and at time intervals as short as one hour. The achieved bias stability $\Delta f/f$ of our optical gyroscope is continuously below 10^{-20} over time intervals of several weeks, demonstrating the strength of optical interferometry. Furthermore, our measurement technique utilizes an entirely different and physically independent measurement concept compared with GNSS and VLBI. We reiterate that an inertial sensor provides a single-point measurement as opposed to a technique that requires a global network of observing stations. A gyro can observe quantities that are not accessible by the other space geodetic techniques, such as the retrograde diurnal polar motion and position of the instantaneous rotation axis of the Earth. The unique capability for a high temporal resolution offers new opportunities for monitoring the Earth's rotation and the identification of the underlying driving geophysical processes down to the sub-diurnal scale. Measurements based on independent techniques are important for the identification of technique-specific systematic errors. Furthermore, a ring laser gyroscope is ultimately sensitive to relativistic precessional effects, such as Lense–Thirring frame dragging¹⁹, which is inaccessible by a star compass. Right now, there is no evidence of a fundamental limitation to this measurement technique.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41566-023-01286-x>.

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Methods

Ring laser operation

The 16 m² ring laser structure rests horizontally on a solid pier, grounded to bedrock in a dedicated underground laboratory. It is enclosed by an atmospheric-pressure-stabilizing vessel, which avoids scale factor variations caused by compressional variations from passing weather patterns. A radio-frequency exciter provides the necessary plasma discharge to a 50:1 helium:neon gas mixture in a 5-mm-diameter gain tube in the middle of one side of the ring cavity. The diameter of the gain tube was chosen to support TEM₀₀, but to discourage higher-order Hermite–Gaussian laser modes. Pressurizing the cavity to 10 hPa increases the homogeneous broadening of the gain curve and enlarges the range where no other longitudinal mode is excited to more than 100.00 MHz, despite a free spectral range of 18.75 MHz. The application of two isotopes, namely, ²⁰Ne and ²²Ne, in a ratio of 1:1 introduces a shift of 800 MHz to the laser transition, which decouples the two counter-propagating laser beams from each other and therefore avoids gain competition. Apart from the four mirrors and the capillary for laser excitation, there are no further loss-creating intracavity components. The nanowatt output of the two counter-propagating laser beams is superpositioned on a beam combiner behind one of the mirrors. The intensity of the clockwise beam is detected by a low-noise photodiode and fed back to the radio-frequency exciter, to stabilize the laser intensity in the cavity. Another photodiode behind the third mirror detects the intensity of the counter-clockwise beam. A low-noise data logger records the beat note and the two laser beam intensities at a rate of 2 kHz. The system autonomously and continuously runs and all the observations are used for the analysis. Only the seismically induced excursions during very strong earthquakes are taken out before postprocessing, when necessary. The operational setup is covered in detail elsewhere^{8,13}.

The sensor model

A ring laser is composed of a travelling-wave cavity, enclosing an area A with a beam in the clockwise direction and a beam in the counter-clockwise direction. Their beat frequency is proportional to the scale factor, the externally imposed rate of rotation Ω and the projection of the angular velocity vector on the normal to the area A , according to

$$\Delta f = \frac{4A}{\lambda P} \Omega \sin \theta, \quad (4)$$

where P is the perimeter and λ is the operation wavelength. For a square gyro aligned with the pole and considering that we need to have an integer number N of waves around the cavity $P = N\lambda$ to satisfy the lasing condition, this expression, according to other work¹⁴, can be rewritten as

$$\Delta f = \frac{N}{4} \Omega \sin \theta. \quad (5)$$

The scale factor can be established with high accuracy. Using an optical frequency comb, referenced to a local hydrogen maser and sensitive microwave detection techniques, we can establish the optical frequency around the cavity to $f = 473,612,708.08 \pm 0.15$ MHz with high accuracy, whereas $N = 25,280,397$ is accurately obtained from the measurement of the cavity's free spectral range. Finally, we need to apply a few corrections to the scale factor. In another work¹⁴, we have derived the required corrections for the Goos–Hänchen area correction factor (I), gas refractive index factor (II), dispersion factor for the mirror coatings and plasma (III) and cavity phase correction (IV) caused by the curvature of the wavefront (Table 1). This table, obtained from an earlier work¹⁴, lists these contributions and their respective error estimates. Combining all these additional small corrections, eventually the accurate beat note of the ring laser can be obtained as

Table 1 | Corrections to scale factor for G

No.	Quantity	Value for G	Estimated uncertainty (ppb)
I	$(1 + 8\gamma/P)$	$1 + 8.78 \times 10^{-8}$	1.6
II	$1/n^2$	$1 - 6.616 \times 10^{-7}$	1.6
III	$1/D$	$1 - 2.527 \times 10^{-7}$	0.2
IV	$1 + \frac{\varphi_0 + \varphi_D}{2\pi N}$	$1 + 4.11 \times 10^{-8}$	0.3

$$\Delta f = \frac{N}{4} \Omega (1 - 7.854(16) \times 10^{-7}) \sin \theta. \quad (6)$$

Backscattering of light at the mirrors causes a weak coupling of the two resonators and pushes or pulls the optical frequency away from its unperturbed position. We observe a non-reciprocal offset from backscatter coupling of up to 4 mHz in our system, which causes an error of 11 ppm on the Sagnac beat note, if not corrected. Utilizing the measured intensities of each beam and the procedure described elsewhere¹⁵, we obtain the unperturbed beat note. The two beams in the cavity do not have the same intensity. The difference in brightness, corrected for the effect of differential amplifier gain, is below 1%. This gives rise to a null-shift bias, which is of the order of 3 ppm and has been corrected with the formalism presented in other work^{16,17}. We have modified this approach by solving for the common gain in the ratio of parameter α (gain minus loss) and β (self-saturation)²⁰ with respect to the measured instantaneous intensity of each beam.

A year-long time series of G exhibits low-frequency excursions with periods usually much longer than one month and amplitudes of the order of 50 μ Hz. These could be the result of a non-reciprocal variable bias from Fresnel drag, Langmuir flow in the gain medium or slowly changing birefringence in the mirror coatings. None of these effects have yet been clearly identified, and we remove most of them by applying a phase-preserving forward–backward high-pass filter with a cut-off frequency of 0.3 μ Hz. The same filter is also applied to the time series of the LoD signal.

The orientation model

The requirements for the accuracy of the tilt corrections are high, as 3 nrad of north–south tilt corresponds to 1 μ Hz in Δf or 0.16 μ rad s^{−1} in the instantaneous rotation rate. With the scale factor established as introduced above, we obtain the orientation of the sensor from the measurements as

$$\theta = \sin^{-1} \left(\frac{\Delta f_{\text{obs}}}{\Delta f_{\text{sensor}}} \right). \quad (7)$$

This conversion is sensitive enough to resolve the initial orientation of the gyro plane with respect to the pole to $\delta\theta \leq 15$ μ rad. With the initial value of the tiltmeters established, we monitor the relative changes in the north–south direction. The ring laser G is resting on a solid pier, rigidly attached to bedrock. The pier is mechanically isolated from the building in which it is housed. Several tiltmeters of the LGM model 1-K type are located side by side near the middle of the Zerodur base plate. The instruments resolve the tilt angles with a resolution of less than 1 nrad. There is a small bias drift on these measurements in the long term as a result of changing temperature and potentially also due to slowly changing humidity at the capacitive readout system. For the three north–south-sensing tiltmeters, we have established a temperature coefficient of -1.4 μ rad K^{−1} for TM1, -1.5 μ rad K^{−1} for TM2 and -1.2 μ rad K^{−1} for TM3. All the tiltmeters show good agreement over periods of one or two weeks. Over longer periods, we notice a small drift, which is removed by the high-pass filter.

Table 2 | Geophysical signals, contained in the ring laser observations

Signal source	Maximum amplitude _{pp}	Signal period	Reduction method
Earth tides	80 nrad	0.5 days	SPOTL library ³
Diurnal polar motion	100 nrad	1 day	Routine established in ref. 10
Annual wobble	0.5 μ rad	365.3 days	Observations from ref. 12
Chandler wobble	1.5 μ rad	434 days	Observations from ref. 12
LoD variation	~1 ms	14 days	GNSS daily finals from ref. 12

The rotation model

To the best of our knowledge, the results reported here are the first direct observations of the high-frequency component of LoD in the frequency domain at around 1 μ Hz with an inertial sensor. To validate the ring laser performance, we compare the ring laser observations with the official data products from the IERS. There are several signal sources contributing to the observations (Table 2). The first two items in Table 2 are reduced from the ring laser observation by subtracting the theoretical models. These models are well tested to a frequency deviation of less than 1 μ Hz in amplitude. A spectral analysis still shows a small frequency component in the diurnal and semi-diurnal frequency windows, which can be attributed to ocean loading and atmospheric loading. These effects are not modelled, because they are small compared with the signal of interest.

Only the combined signal contribution of the Chandler and annual wobbles act at frequencies below the cut-off frequency of the high-pass filter, and it is about one order of magnitude larger than the experienced drift. Therefore, the Chandler and annual motion values are taken from the C04 time series of the IERS, converted to the Sagnac contribution; this correction is applied before the high-pass filter is utilized. Relevant data files, including those containing the tilt, null-shift and backscatter correction values are available elsewhere²¹.

Data availability

The necessary data files and brief file descriptions, raw data files and some relevant auxiliary files are available via Figshare at <https://doi.org/10.6084/m9.figshare.23684520>. Source data are provided with this paper.

Code availability

The analysis program was graphically coded in LabView and is a complex suite that is neither simple nor fully intuitive to run. It is available

via Zenodo at <https://doi.org/10.5281/zenodo.8146323>, but we recommend that users contact the corresponding author before use. The basic dataset for this publication is available via Zenodo at <https://doi.org/10.5281/zenodo.8146444>.

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Author contributions

All authors contributed in a meaningful way to the development of the sensor setup over an extended period of time. K.U.S. and J.K. carried out the measurements. K.U.S. provided the analysis and wrote the manuscript. J.-P.R.W. co-wrote the manuscript. T.K. provided the tilt corrections and atmospheric attraction correction model. U.H. provided and verified the geodetic correction methods.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41566-023-01286-x>.

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